

## **Evolution of an intra-plate rift basin: the Latest Jurassic-Early Cretaceous Camerós Basin (Northwest Iberian Ranges, North Spain)**

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## Introduction to the Basin

The main objectives of this field trip to the Cameros Basin (Fig. 1) are to visit seismic scale outcrops, and to analyse the stratigraphy and sedimentology of pre-rift marine deposits and syn-rift lacustrine, fluvial and alluvial depositional systems. The trip will go through three transects to the Cameros Basin, along which, vertical and lateral variations of the sedimentary record and both, extensional and contractional tectonic structures, will be observed. The hydrocarbon geology of this area (reservoirs, source rocks, oil seeps, and thermal events) will be also discussed.

The Cameros Basin is located in the Northwest of the Iberian Chain (Fig. 1A). This is one of the basins forming part of the Mesozoic Iberian Rift System or Iberian Basin (Mas et al., 1993; Guimerà et al.,

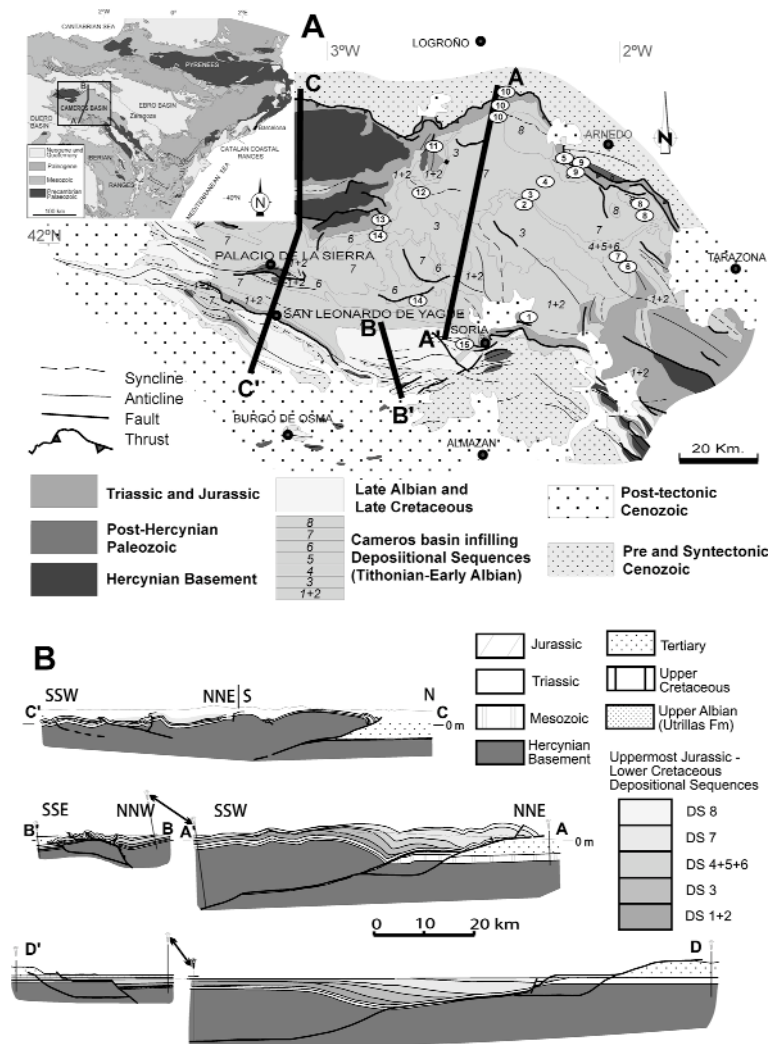


Figure 1. A. Geological map of the Cameros Basin. A-A', B-B' and C-C': Location of cross-sections of Fig. 1B. B. A-A', B-B', and C-C': geological cross-sections through the Cameros basin. D-D': partial restoration of cross sections A-A' and B-B' at the previous state of basin inversion. See Fig. 1A for location. Modified from Guimerà et al. (1995).

1995; Salas et al., 2001; Mas et al., 2002). In the Iberian Basin two rifting cycles can be distinguished from the late Permian to the late Cretaceous (Alvaro et al., 1979; Vilas et al., 1982; Salas and Casas, 1993; Roca et al., 1994; Salas et al., 2001; Mas et al., 2004): 1) a Permo-Triassic Rift, Late Permian to Hettangian; and 2) a Latest Jurassic-Early Cretaceous Rift, Kimmeridgian (southeastward) or Tithonian (northwestward) to Early Albian (Fig. 2). During the Latest Jurassic-Early Cretaceous Rift cycle four sub-basins up to 3-6.5 km thick developed in the Iberian Rifting, being the Cameros Basin the most subsident (Mas et al., 1993). The Iberian Rift System was inverted during the Paleogene generating the Iberian Chain (Salas et al., 2001), which is a fold-and-thrust belt whose overall structure is defined by two NW-SE trending arches.

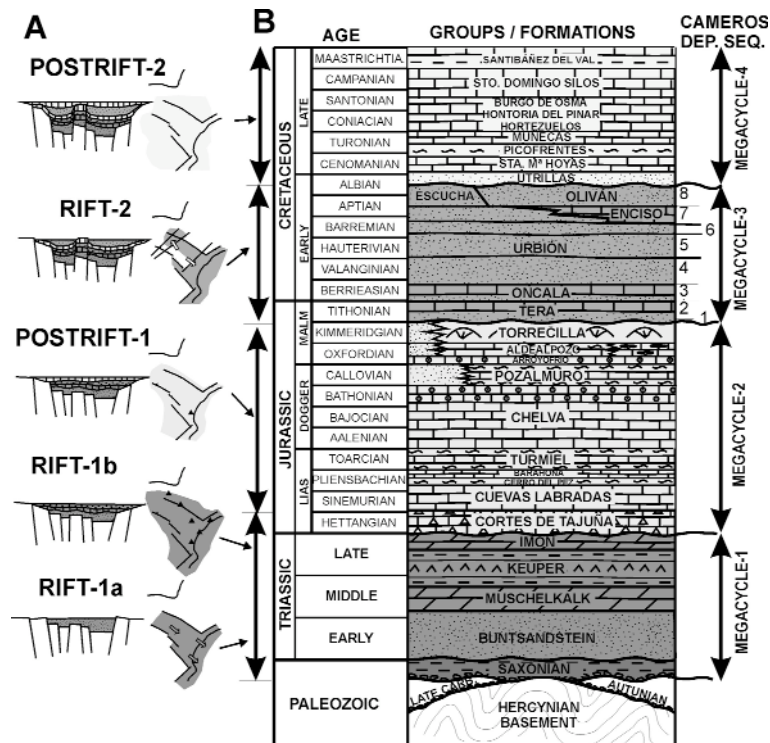


Figure 2. A. Rift cycles and Post-rift stages on the evolution of the Iberian Basin (modified from Salas et al., 2001). B. Idealized and synthetic sketch/lithostratigraphic section showing the latest Paleozoic and Mesozoic stratigraphic units at the Cameros area (North Iberian Range). From Mas et al. (2003).

The Cameros tectonic Unit includes the Cameros Basin fill, its Mesozoic substratum and the Variscan basement, which crops out to the northwest and southeast. The structure of the Cameros Unit is characterized by (1) a major newly formed north-verging thrust sheet, which has a horizontal displacement of up to 30 km and overrides the Tertiary Ebro Basin; and (2) a conjugate, south-verging imbricate fan fold-and-thrust system that encroaches on the Almazán Basin (Fig. 1B, B-B'; Mas et al., 1993; Guimerà et al., 1995; Mas et al., 2002).

The Cameros Basin is atypical, if compared to other basins of the Chain. It is a synclinal basin (Mas et al., 1993; Guimerà et al., 1995) with no major fault bounding during its development (Fig. 1B, A-A'). It is interpreted as an extensional-ramp basin (Mas et al., 1993; Guimerà et al., 1995; Mas et al., 2002). This basin is also the only one of the Mesozoic basins in the Chain in which deposits have been partially affected by metamorphism. A large proportion of deposits of the eastern sector of the basin has been affected by low-grade to very low-grade metamorphism. Findings based on a detailed study of the basin combining mineralogical, petrological, geochemical and structural approaches, have defined the metamorphism as hydrothermal and allochemical (Casquet et al., 1992; Barrenechea et al., 1995, 2000; Alonso-Azcárate et al., 1995, 1999; 2001; Mantilla et al., 1998, 2002; González-Acebrón et al., 2010). The most important conclusions to be drawn from these studies are: (1) metamorphism displays very clear thermal inversions in the depocentral areas, and the grade reached is influenced by the changes in permeability and composition of the sediments rather than by the burial depth; (2) metamorphism postdates the basin fill and comprises two different hydrothermal events: The first one dated as Late Albian to Coniacian (-106 to -86 Ma), and a second event dated as Lower to Mid Eocene; (3) the metamorphic conditions range from low-grade or epizone to very low-grade or anchizone, with a maximum temperature of 350-370°C and a maximum pressure of 1 kbar, at the first metamorphic peak.

## **The Mesozoic Substrate of the Cameros Basin**

The Late Permian and Mesozoic evolution of the Iberian Rift System has been divided into four major rift cycles and post-rift stages (Salas et al., 2001) (Fig. 2A). In the NW sector of the Iberian Chain four megacycles or depositional supersequences have been distinguished: the Late Permian to Triassic Megacycle 1; the Early to Late Jurassic Megacycle 2; the Latest Jurassic to Early Cretaceous Megacycle 3; and the Late Cretaceous Megacycle 4 (Guimerà et al., 2004; Fig. 2B). The first two megacycles correspond to the “Mesozoic” substrate of the Cameros Basin. During the Late Permian-Triassic Megacycle 1, the development of the Iberian Basin started with the reactivation of late-Variscan faults (Vegas and Banda, 1982). As a consequence, Late Permian and Triassic deposits unconformably overlie the Variscan basement. The Early to Late Jurassic Megacycle 2 was dominated by thermal subsidence and very extensive carbonate platforms developed (Alonso and Mas, 1990; Salas et al., 2001).

Several depositional sequences have been identified in this megacycle at the northwestern sector of the Iberian Chain, the last of which, the Early Kimmeridgian Sequence, generally constitutes the substratum of the Latest Jurassic-Early Cretaceous syn-rift sequences of the Cameros Basin (Fig. 2B). The Early Kimmeridgian was a period of global sea level rise (e.g. Haq et al., 1987), which is apparent throughout the Iberian and North Tethys domain. Sedimentation in the Iberian Basin mainly occurred in a shallow carbonate storm-dominated ramp which was opened southeastwards to the Tethys and northwards to the boreal realm (Alonso and Mas, 1990; Bádenas and Aurell, 2001; Benito

et al., 2005). The connection between both domains was located in an epicontinental seaway (the Soria Seaway, Bulard, 1972), generated between the Iberian and the Ebro massifs. Sedimentation in this seaway was characterized by the development of coral reefs of the Torrecilla en Cameros Fm. The growth geometry of these reefs was different towards the northern and southern parts of the basin, because it was controlled by both the prevailing positive eustatic conditions during Kimmeridgian times, and by the basin tectonics (Alonso et al., 1986-1987; Benito et al., 2001, Benito and Mas, 2002, 2006).

### The Cameros Basin fill (Rift cycle 2): The Latest Jurassic - Early Cretaceous Megacycle 3

The basin fill (Rift 2; Fig. 2A), which extended from the Tithonian to the Early Albian, corresponds to a large cycle or megasequence bounded by two main unconformities (Figs. 2B, 3). The stratigraphic gap of the lower unconformity is more important in the northern part of the basin than in the central and southern areas (Fig. 3) (Mas et al., 1993; Benito and Mas, 2002; Arribas et al., 2003). The upper limit is the intra-Albian unconformity bounding the base of the Late Cretaceous Megacycle 4 of the Iberian Ranges (Figs. 2B, 3), when large carbonate platforms occupied the Iberian realm (Alonso et al., 1989; Alonso et al., 1993).

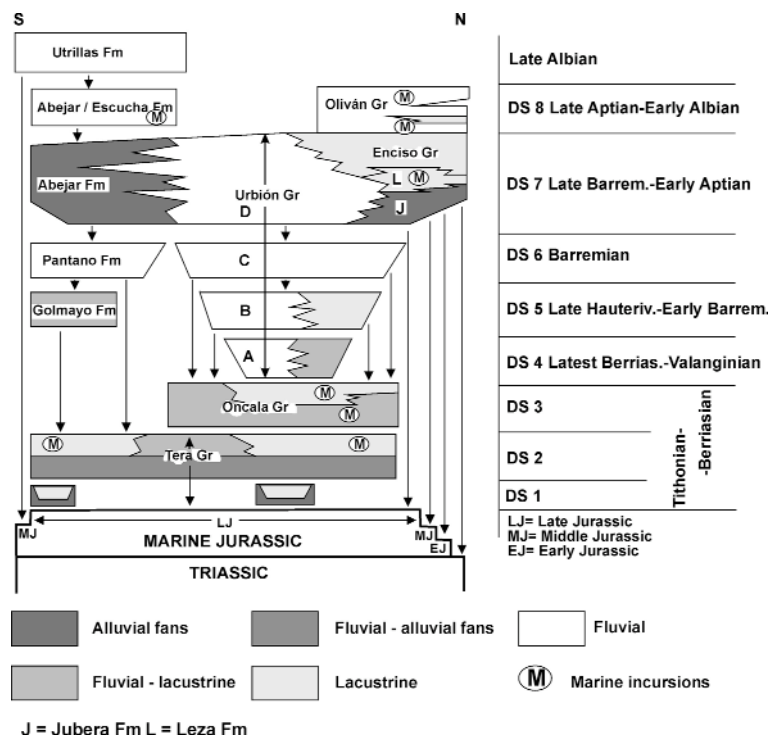


Figure 3. Simplified stratigraphy of the Depositional Sequences (DS) which fill the Cameros basin. Modified from Guimerà et al. (1995).

## *Depositional Sequences*

The Latest Jurassic-Early Cretaceous megacycle or supersequence filled the basin through eight depositional sequences bounded by unconformities (Mas et al., 1993; Mas et al., 1997; Mas et al., 1998; Martín i Closas and Alonso Millán, 1998; Mas et al., 2002; Arribas et al., 2003) (Fig. 3). This sedimentary record consists mainly of continental sediments corresponding to alluvial and lacustrine systems, with some marine influence (Guiraud and Seguret, 1985; Gómez Fernández, 1992; Alonso and Mas, 1993; Quijada et al., 2010; Suarez-González et al., 2010; Figs. 3, 4). In general, all the depositional sequences are very thick, especially DS 2 and DS 3 of Tithonian-Berriasian age (more than 2000m of sediments each); and DS 7 and DS 8 of Barremian-lower Albian age (up to 2500 and 2800m, respectively). Sequences are usually arranged into sedimentary cycles starting with alluvial clastic deposits, which evolve upwards to lacustrine limestones (Figs. 3, 4). Paleocurrent data (Fig. 4) and petrofacies composition of siliciclastic intervals at the Southwestern basin margin, reveal that the siliciclastic input mainly came from the Iberian Massif (Mas et al., 1997; Arribas et al., 2003; 2007).

Chronostratigraphic data are not yet complete due to poor fossil record and local metamorphism. The main data are based on charophytes, ostracods, palynological associations for the continental record, and a few marine calcareous algae (mainly *Dasyclad*) from the marine incursions (Brenner, 1976; Guiraud and Seguret, 1985; Schudack, 1987; Clemente et al., 1991; Alonso and Mas, 1993; Martín i Closas and Alonso Millán, 1998; Schudack and Schudack, 2009; Suárez-González et al., 2010). Ages for the different sequences are shown in figure 3.

## *Facies and Sedimentary Environments*

Proximal facies are commonly developed towards the southwest margin (Figs. 3, 4). These deposits are essentially formed by alluvial facies associations of sandstones and conglomerates corresponding to braided systems. The more distal deposits, mainly lacustrine carbonates and shales, are generally displaced towards the northeastern margin (Fig. 4). One of the more characteristic facies associations correspond to lacustrine-palustrine cycles of relatively permanent shallow carbonate lakes, which occasionally accumulated major quantities of organic matter. Another distal facies association is carbonate-evaporite laminites, corresponding to shallow ephemeral lakes (Fig. 4). Locally, laminated carbonate facies are associated with black-shales, which presumably corresponds to shallow lacustrine areas with high organic matter input. Between the areas of proximal alluvial systems and those of distal carbonate lakes, meandering fluvial systems developed (Fig. 4).

In some of the sequences there is evidence of sporadic marine incursions from the Southeast (Tethys), especially during global high sea level intervals (e.g. Alonso y Mas, 1988; 1993) as the Tithonian-Berriasian and the Barremian-Aptian (Figs. 3, 4). These incursions produced the development of coastal lakes containing benthic forams and

Dasycladal algae (Alonso and Mas, 1993; Suarez-González et al., 2010). In the siliciclastic units (DS 3 and DS 8) the sea incursions lead to tidal-influenced depositional environments (Quijada et al., 2010).

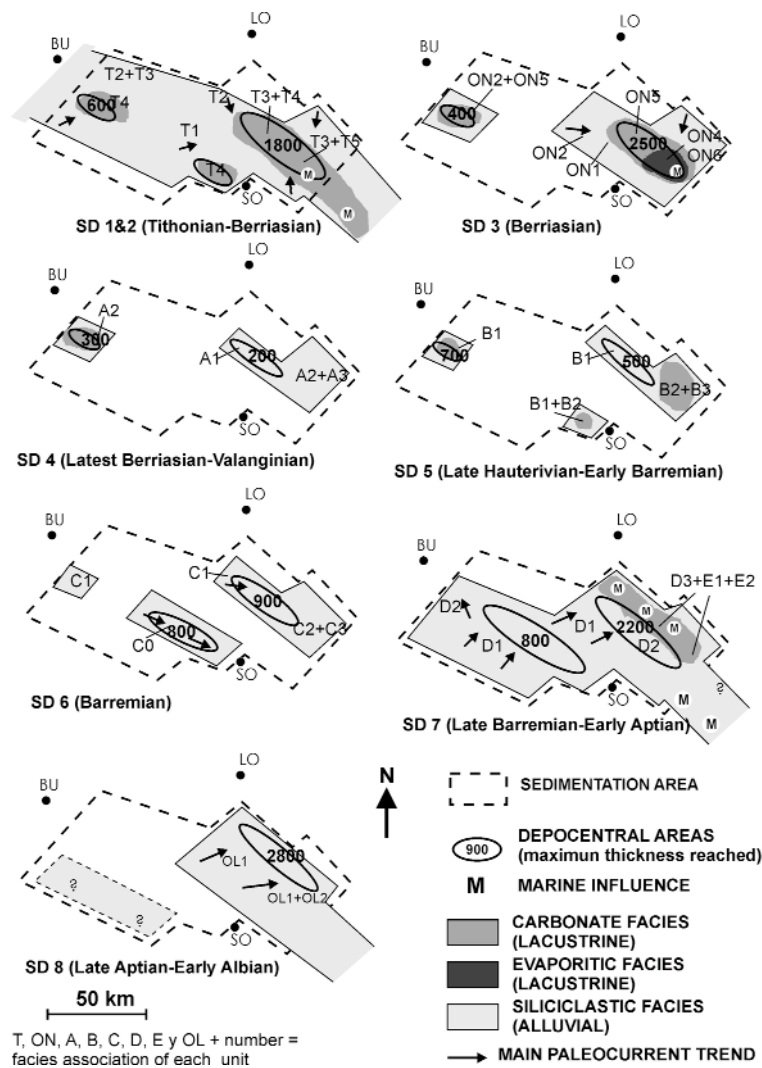


Figure 4. Schematic palaeogeographic evolution of the Cameros Basin. BU: Burgos, LO: Logroño; SO: Soria. Modified from Mas et al. (1997).

### Geometry of the basin fill

The different depositional sequences that filled the basin lie unconformably on the Mesozoic substratum (Fig. 1B). The architecture of basin infill suggests a progressive migration of the depocentres of the successive depositional sequences towards the North, lying in on-lap with respect to the previous sequences. Thus, the maximum thicknesses are achieved in the Northeastern area of the basin (9500 m) (Mas et al., 1993; 2002), with a maximum vertical thickness of up to 6.5 km (Fig. 2B). It should be noted that no major faults have been found in the Northern margin of the basin to explain such a large thickness. In the

southern part of the basin the first sequences (DS 1 to DS 3, Tithonian-Berriasian) lie in on-lap with respect to the Kimmeridgian reefal complexes of the Torrecilla en Cameros Fm. In the northern area, however, DS 7 (Late Barremian-Early Aptian) sequence lies unconformably on the Kimmeridgian Torrecilla Fm. (Fig. 1B).

## Evolution of the Cameros Basin: Basin Model

The Cameros Basin is a synclinal basin and no major faults bounded it during its development (Fig. 1A). The idea of a major extensional fault that surfaced at the northern boundary of the basin can be rejected because of the great continuity of the Jurassic substratum of the basin. In turn, the northward migration of the depocenters of the successive depositional sequences and its lapping on the pre-basin Mesozoic substratum (mainly, marine Jurassic) (Fig. 1B), may be explained by assuming that the basin formed over a roughly south dipping ramp in a horizontal extensional fault (Fig. 1B). That is the Cameros Basin corresponds to an extensional-ramp basin (Mas et al., 1993; Guimerà et al., 1995; Mas et al., 2002). Indeed, in scale models (McClay, 1990; Roure et al., 1992), similar patterns of infill units in a synclinal basin have been obtained by horizontal-extensional faults containing ramp segments over which the basin was developed (Mas et al., 2003: Fig. 22).

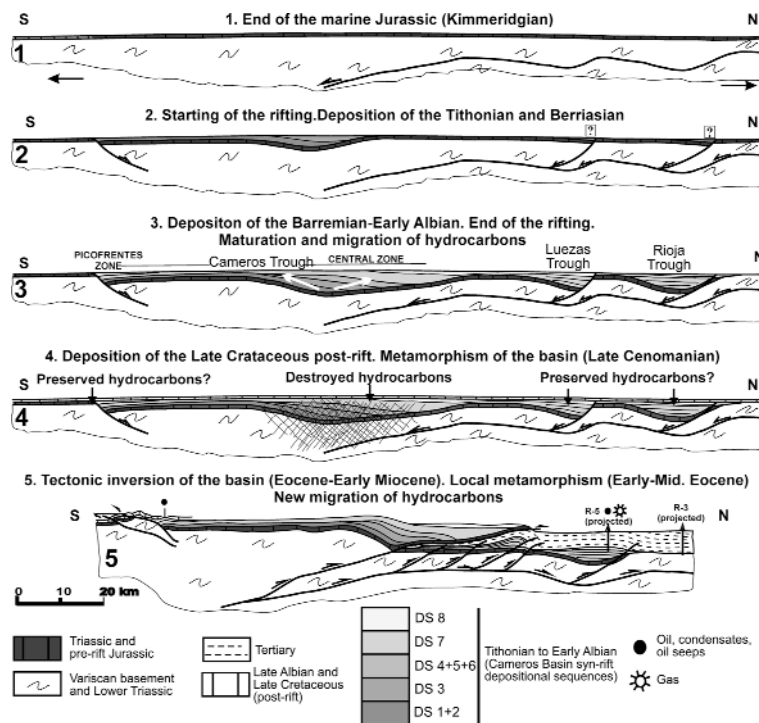


Figure 5. Schematic evolutionary model for the Cameros Basin. Modified from Mas et al. (2003).



One important question is the depth at which the extensional fault was located. To get round the problem, it has been suggested that the extensional fault is located deep inside the Variscan Basement (Fig. 5) at a depth of 7 to 11 km (Mas et al., 1993; Guimerà et al., 1995). The Cameros basin could have been produced by the motion of a deep extensional fault containing two nearly horizontal sections (flats) separated by an intermediate section dipping to the south (ramp). The direction of displacement for the hanging wall was S-SW, parallel to the direction of the basin extension (Fig. 5). Thus, the Cameros Basin is interpreted as a hanging-wall basin that constitutes a good real equivalent of the extensional-ramp basin scale model of McClay (1990).

Basin inversion took place during the Paleogene to the Early-Middle Miocene due to Pyrenean compression (Guimerà et al., 1995). The Cameros Basin appears at present as a pop-up structure bounded by the Cameros thrust to the North and a minor back-thrust system to the south (Figs. 1B, 5). The main Northern thrust is a newly formed fault. Its formation would have been facilitated by: (1) sealing of the Mesozoic extensional fault beneath the basin as a result of Late Cretaceous metamorphism, and (2) the presence on the northern flank of the basin of a potential weakness zone located in the Keuper beds. From this weak zone, the new thrust could have nucleated and spread to the North and to the South during deformation. The thrust system to the South of the basin (Fig. 5) developed from the inversion of the minor normal faults which bounded the Mesozoic basin towards the South (Fig. 1B).

## GEOLOGICAL ITINERARY

The maps (Figs. 6, 7) show the locations of the places to be visited during the fieldtrip (stops 1 to 15). Figure 8 includes the chrono- and litho-stratigraphic location of each stop. The explanation of these locations is given on the following pages.

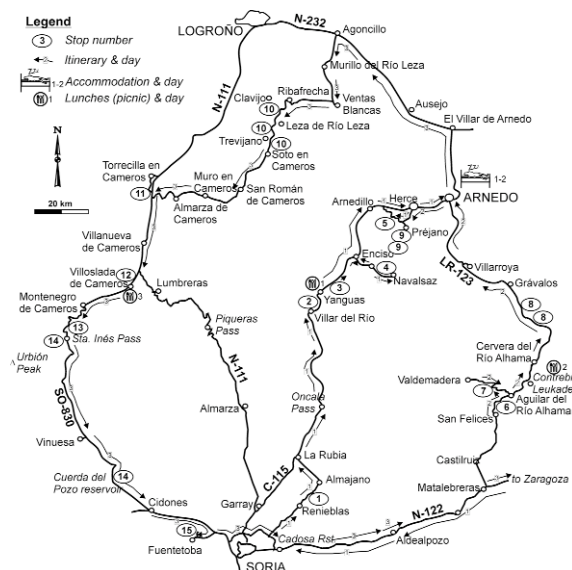


Figure 6. Fieldtrip itinerary and stops.

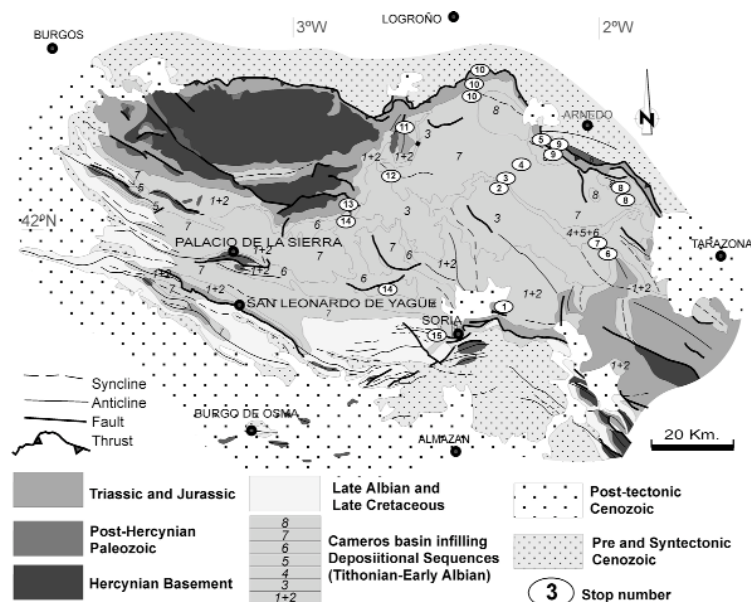


Figure 7. Location of the fieldtrip stops on the schematic geological map of the Cameros Basin. Modified from Mas et al. (2003).

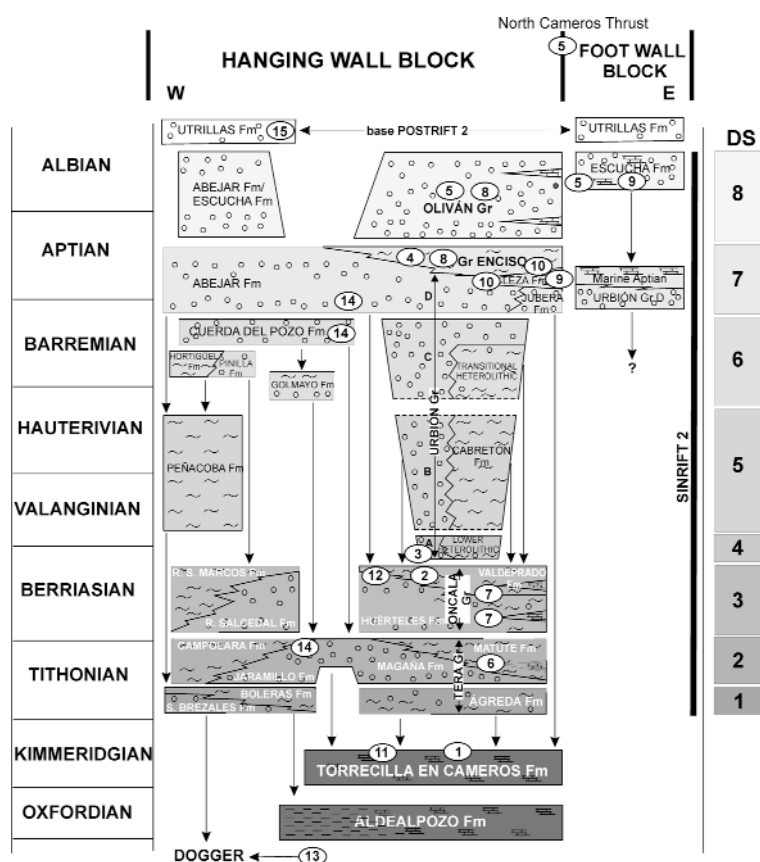


Figure 8. Location of the field trip stops in the stratigraphic record of the Cameros Basin. Modified from Mas et al. (2004).

## **FIRST DAY: GENERAL S-N CROSS SECTION ACROSS THE DEPOCENTRAL AREA OF THE CAMEROS BASIN.**

### **Stop 1**

*Renieblas (Soria province): The southern border of the  
Cameros Basin*

*Location:* On the road SO-V-1001 between the localities of Renieblas and Almajano (Soria province). UTM coordinates, datum WGS84, zone 30 between: x=552988; y=4631257 and x=553342; y=4631537 (Figs. 6, 7, 8).

*Objectives:* Introduction to the basin; Early Kimmeridgian coral-bearing and oolitic pre-rift carbonate sequence. The first syn-rift continental sequence (DS 1) overlies the marine pre-rift sequence.

*Description:* Close to Renieblas, at the southern border of the Cameros Basin, the lower part of Ágreda Fm (first syn-rift sequence DS 1, Tithonian ) overlies marine carbonates of the Torrecilla en Cameros Fm (pre-rift Early Kimmeridgian Sequence). The Torrecilla en Cameros Formation was deposited in a storm-dominated ramp and comprises coral-bearing and oolitic carbonates (Figs. 9, 10). The Ágreda Fm corresponds to distal alluvial fan deposits with intervening conglomeratic paleochannels, calcretes and some shallow lacustrine carbonate beds.

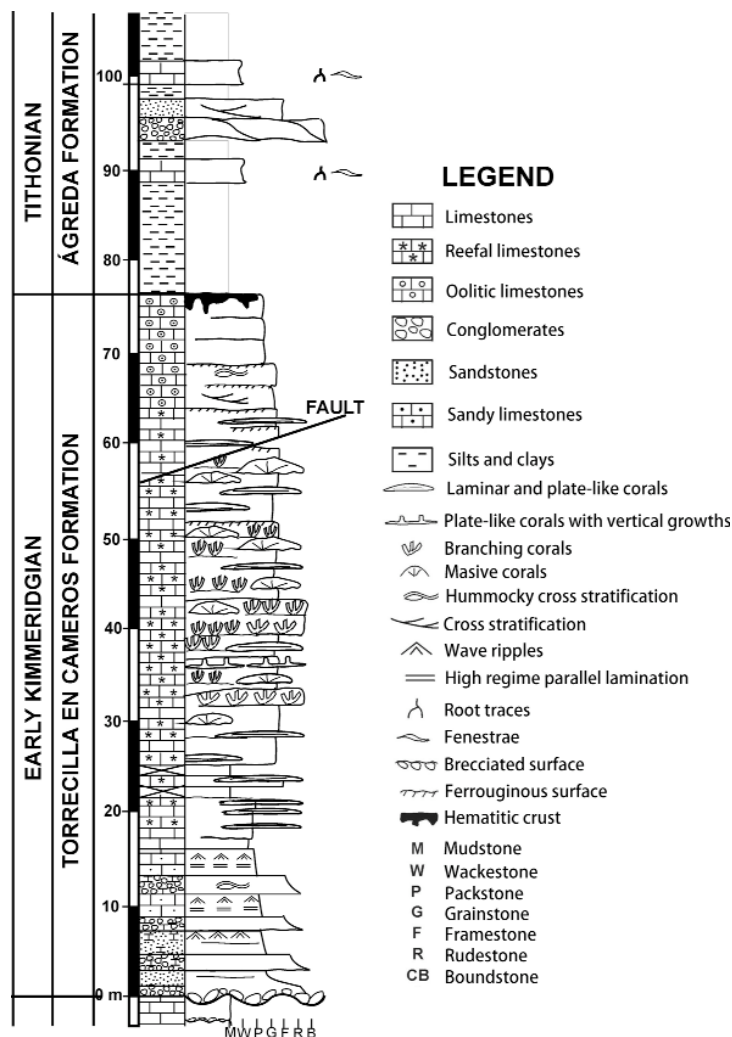


Figure 9. Simplified stratigraphic section of Torrecilla en Cameros Fm (Early Kimmeridgian) and the lowermost part of Agreda Fm at Renieblas (Soria sector). From de Benito and Mas (2002).

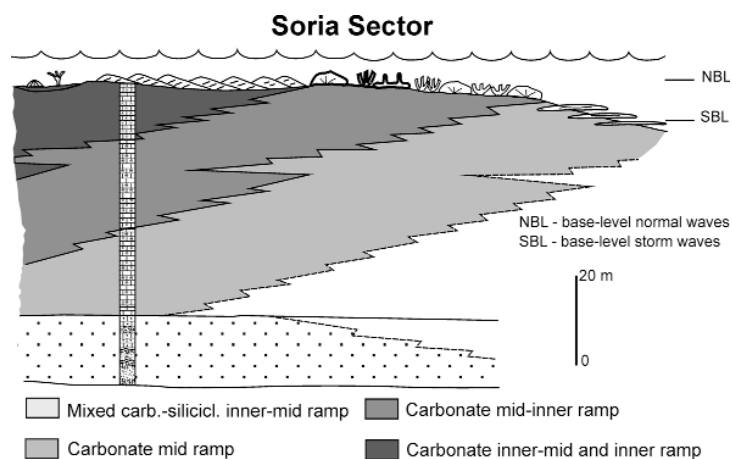


Figure 10. Idealized sketch illustrating the sedimentary evolution of the reefal complexes of the Torrecilla en Cameros Fm in the Soria sector. Modified from Benito and Mas (2002).

## Stop 2

### *Villar del Río - Yanguas (Soria): DS 3 (Berriasian) lacustrine facies*

**Location:** On the road SO-615 between the localities of Villar del Río and Yanguas (Soria province), very close to Yanguas. UTM coordinates, datum WGS84, zone 30 between: x=554967; y=4660455 and x=554828; y=4660795 (Figs. 6, 7, 8).

**Objectives:** Lacustrine laminated carbonates, black shales and their role as hydrocarbons source rocks.

**Description:** Close to Yanguas, at the depocenter area of the Cameros Basin, the upper part of DS 3 (Valdeprado Fm, Berriasian) is composed of thinly laminated carbonates interbedded with black shales (Fig. 11). Laminated carbonates contain pseudomorphs after sulphates, stromatolites and veins of calcite, quartz and native sulphur. They are interpreted as deposited in shallow carbonate-evaporite coastal lakes. Black shales correspond to lacustrine areas with high organic matter input where environmental conditions became anoxic.

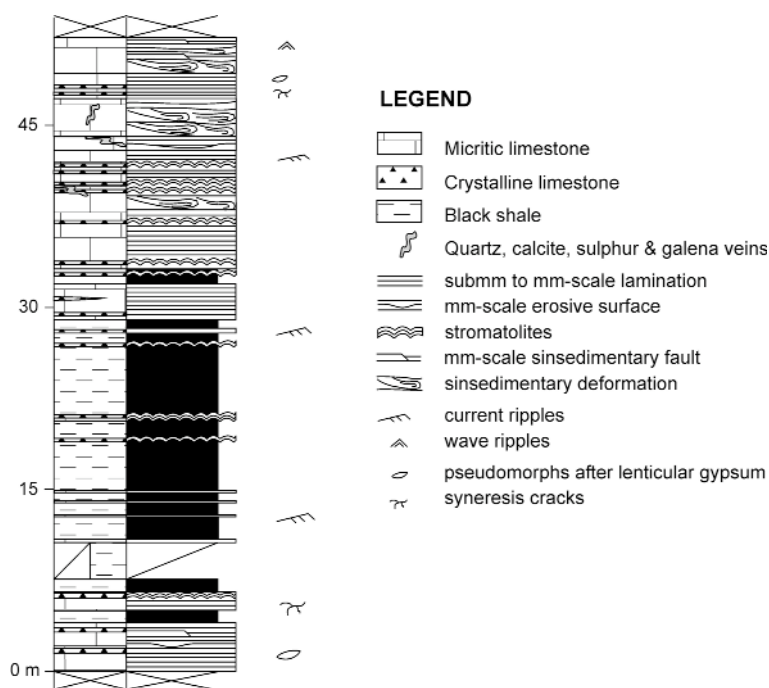


Figure 11. Partial stratigraphic section of Valdeprado Fm (upper part of DS 3; Berriasian) at Yanguas (Soria). From Quijada et al. (in press).

### Stop 3

*Yanguas (Soria): Fluvial systems and source areas in DS 4, DS 5, DS 6 and lower part of DS 7 (Latest Berriasian to Barremian). Hydrothermal metamorphism of the basin*

*Location:* On the road SO-615 just to the North of the town of Yanguas. UTM coordinates, datum WGS84, zone 30 between: x=555077; y=4661593 and x=555343; y=4661778 (Figs. 6, 7, 8).

*Objectives:* Fluvial systems as hydrocarbons reservoirs. Hydrothermal events and ages of the metamorphism.

*Description:* Less than 1 km to the North of the town of Yanguas there is the contact between the carbonate laminites and black shales of the Valdeprado Fm, and the fluvial systems of the Urbión Group (Latest Berriasian to Barremian; DS 4, DS 5, DS6 and lower part of DS 7; Fig. 12). This sector corresponds to the main depocenter area of the basin and was affected by low grade hydrothermal metamorphism (Fig. 13). Compositional characteristics of sandstones and deduced diagenetic processes suggest that these fluvial systems acted as reservoirs of hydrocarbons; however hydrocarbons were later destroyed due to metamorphism (Fig. 5).

### Stop 4

*Enciso (La Rioja): Siliciclastic-rich shallow carbonate lakes in the upper part of DS 7 (Barremian to Early Aptian). Dinosaur footprints sites of the Cameros Basin*

*Location:* Town of Enciso and the road between Enciso and the town of Navalsaz (LR-356). UTM coordinates, datum WGS84, zone 30 at x=561500; y=4665272 (Valdecevilla dinosaur ichnites site) and at x=563571; y=4664075 (Poyales dinosaur ichnites site) (Figs. 6, 7, 8).

*Objectives:* Dinosaur footprints sites at siliciclastic-rich shallow carbonate lakes.

*Description:* The Enciso Gr (upper part of DS 7, Barremian-Early Aptian) is mainly composed of carbonates and marls, which contain abundant ostracods and also bivalves and gastropods, that were deposited in siliciclastic-rich shallow carbonate lakes (Fig. 14). Deposits of the Enciso Gr contain some of the worldwide known dinosaur footprints sites, as those we will visit, very close to the town of Enciso.

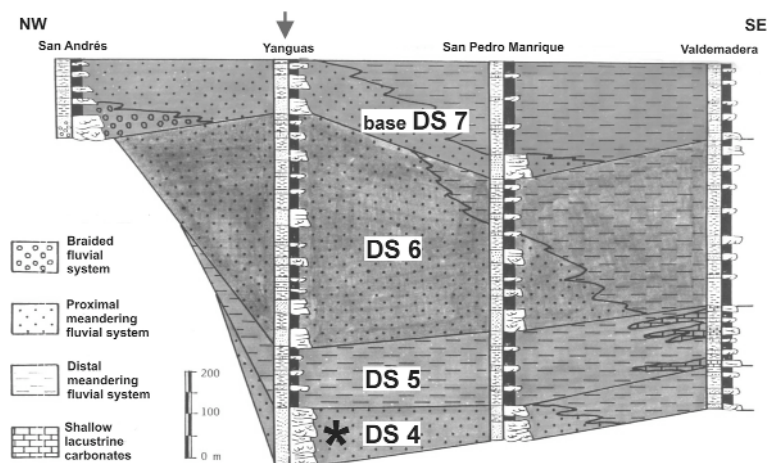


Figure 12. Urbión Group: distribution of the fluvial systems in the central area of the basin. DS 4 at Yanguas section is indicated with an asterisk. Proximal facies are dominant towards the W. Modified from Barrenechea et al. (1995).

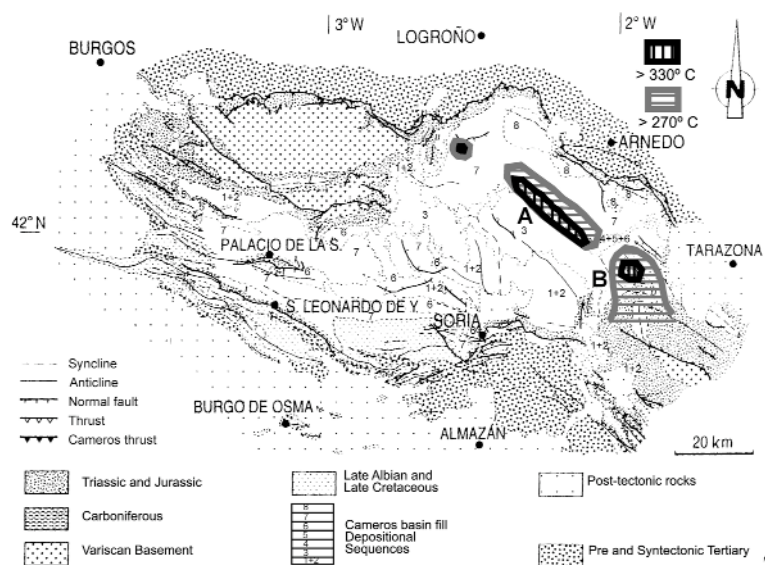


Figure 13. Schematic Geological map of the Cameros Basin showing the areas affected by low and very low grade metamorphism. A. Yanguas - San Pedro Manrique area. B. El Pégado anticline area. Modified from Mas et al. (2002).



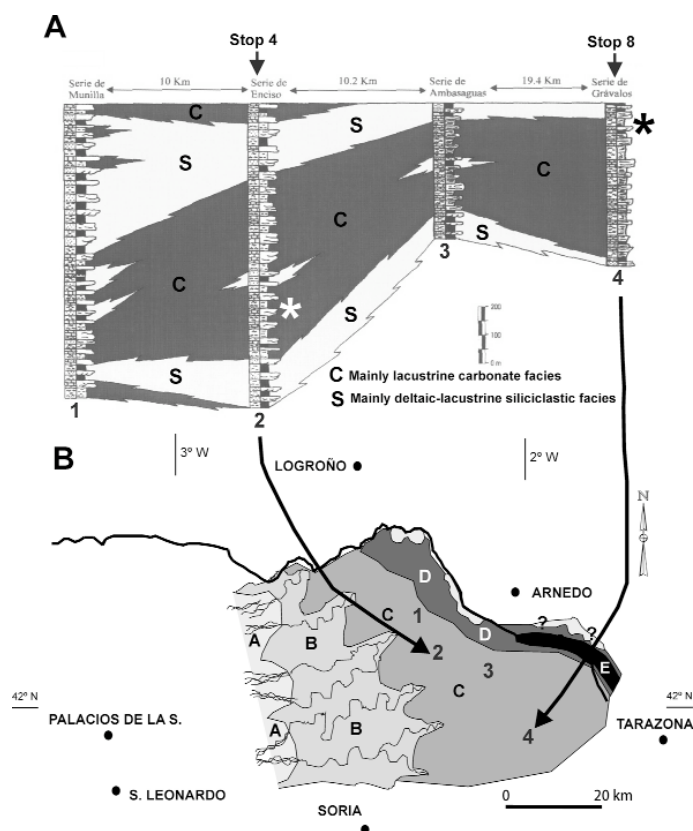


Figure 14. **A.** Siliciclastic-rich shallow carbonate lakes facies distribution in the Enciso Gr (asterisks correspond to stop points); **B.** Paleogeography of the upper record of DS 7 (Late Barremian-Early Aptian). A y B = Urbión Gr D, Aluvial-fluvial systems (A. proximal; B. distal). C y D = Enciso Gr, Carbonate lacustrine systems (C. with strong siliciclastic influence - Enciso Gr s.s.; D. with very little siliciclastic influence and marine incursions - Leza Fm; E. Carbonate shallow marine inner environments - Early Aptian Urgonian carbonate platform). Modified from Mas et al. (2008).



Figure 15. Footprints of Theropod dinosaur recorded on palustrine areas of shallow carbonate lacustrine systems with strong siliciclastic influence. Upper part of DS 7 (Enciso Group; Late Barremian-Early Aptian).



## Stop 5

*Peñalmonte (La Rioja): a) Structure of the Cameros Northern Thrust; b) Late Aptian-Early Albian fluvial to fluvial-deltaic sequence (DS 8) in the hanging-wall of the thrust*

*Location:* The Peñalmonte Peak. On the forest track that connects the road between Prójano and Arnedillo with the town of Navalsaz. UTM coordinates, datum WGS84, zone 30: a) x=564835; y=4671653 and b) x=563085; y=4672353 (at the bench mark Encineta 1098 m, close to a place with several antennas) (Figs. 6, 7, 8).

*Objectives:* The Cameros Northern Thrust and the impressive thickness of the Syn-rift Depositional Sequences of the Cameros Basin.

*Description:* a) Structure of the Cameros Northern Thrust (Fig. 16). Impressive view of the Cameros Northern Thrust, in which the Triassic Keuper evaporites and the marine Jurassic are superimposed to the Late Aptian-Early Albian syn-rift unit (DS 8) and the Paleogene in the foot-wall of the thrust. b) Panoramic view of the very thick Barremian-Early Albian sequences (DS 7 and DS 8) in the hanging-wall of the thrust. DS 7 lies in on-lap with respect to the marine Jurassic and DS 8 lies in on-lap with respect to DS 7.



## SECOND DAY: MAIN CHARACTERISTICS OF THE EASTERN SECTOR OF THE CAMEROS BASIN

### Stop 6

*San Felices (Soria) - Aguilar del Río Alhama (La Rioja):  
a) Panoramic view of the eastern general stratigraphic-  
section; b) Lacustrine facies in the upper part of DS 2  
(Tithonian)*

*Location:* On the road SO-691 between the localities of San Felices and Aguilar del Río Alhama (Soria province). UTM coordinates, datum WGS84, zone 30; a) x=580415; y=4644137 and b) x=582380; y=4646100 (Figs. 6, 7, 8).

*Objectives:* General stratigraphic record at the eastern part of the basin. Distal facies for most of the depositional sequences.

*Description:* a) Panoramic view of the stratigraphic section to be observed during the day (DS 2 and DS 3, Tithonian-Berriasian) at the Alhama River valley (Fig. 17). DS 2 is composed of fluvial sandstones and lutites evolving upwards to carbonate-evaporite lacustrine facies. DS 3 is composed of thinly laminated and brecciated carbonates and evaporites. b) Lacustrine carbonate facies at the top of DS 2 (Tithonian) will be observed in detail (Fig. 18). They are composed of carbonates, containing abundant stromatolites and calcite and quartz pseudo-morphs after evaporites. Mud cracks are also frequent.



Figure 17. General panoramic view of the Cameros Basin fill at its eastern sector. At first plane Magaña Fm and Matute Fm of Tera Gr are observed (DS 2, Tithoniense); at second plane Oncala Gr (DS 3, Berriasian).

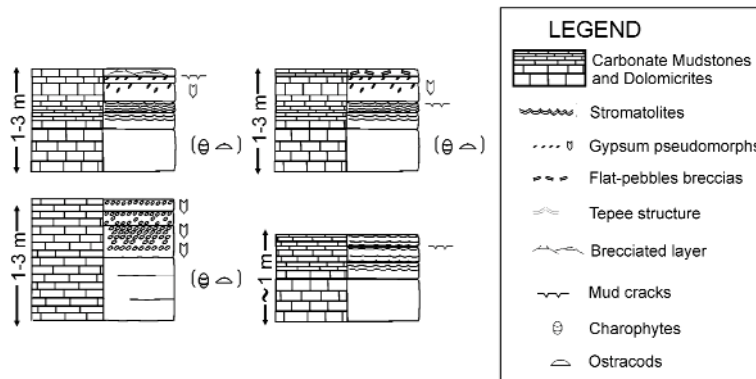


Figure 18. Characteristic facies associations of the upper part of DS 2 (Matute Fm; Tithonian) at Aguilar del Río Alhama (Soria) Sector. Carbonate-evaporite shallowing-upwards sequences deposited shallow lakes (playa- lakes). Modified from González-Acebrón (2009).

## Stop 7

### *Aguilar del Río Alhama - Valdemadera (La Rioja): Shallow carbonate-evaporite coastal lakes in DS 3 (Berriasian)*

*Location:* On the road LR-490 between the localities of Aguilar del Río Alhama and Valdemadera (La Rioja province). UTM coordinates, datum WGS84, zone 30; a) x=580913; y=4646965 and b) x=580786; y=4647697 (Figs. 6, 7, 8).

*Objectives:* Thinly laminated carbonates and evaporites (DS 3, Berriasian) deposited in shallow coastal-lakes.

*Description:* a) At the eastern area of the basin DS 3 is up to 2500 m thick (Fig. 17) and it is mainly composed by thinly laminated carbonates and gypsum (Fig. 19) interpreted as deposited in shallow coastal lakes. Carbonates commonly contain abundant pseudomorphs after evaporites, mud cracks and breccias. b) Intra-formational breccias and disharmonic folds associated with playa-lake and sabkha deposits (Fig 19). An impressive general panoramic view of the basin is observed towards the Pégado anticline (Fig. 20).

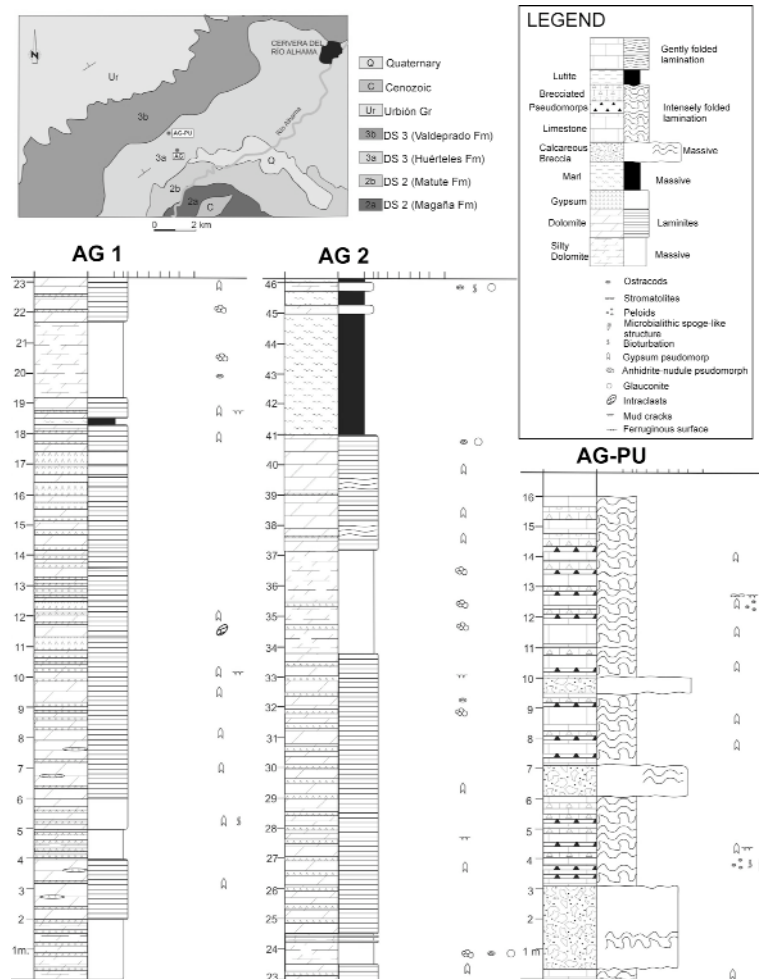


Figure 19. Partial stratigraphic sections of the Huérteles Fm (lower part DS 3; Berriasian) at Águilar del Río Alhama (Soria). From Quijada et al. (in press).



Figure 20. A splendid panoramic view of the basin is observed looking towards the Pégado Anticline from the Aguilar del Río Alhama - Valdemadera road.

## Stop 8

### *Cervera del Río Alhama - Grávalos (La Rioja): General stratigraphic-section from DS 4 to DS 8 (Latest Berriasian-Early Albian)*

*Location:* Along the road LR-123 between the localities of Cervera del Río Alhama and Grávalos (La Rioja). UTM coordinates, datum WGS84, zone 30: (a) x=584878; y=4658225 (b) x=584116; y=4660463 (Figs. 6, 7, 8).

*Objectives:* Carbonate lacustrine systems with siliciclastic influence (Enciso Group, upper part DS 7) and meandering fluvial systems (Oliván Group, DS 8).

*Description:* Cross stratigraphic section of the Cameros Basin sedimentary record in its easternmost area: a) carbonate lacustrine systems with siliciclastic influence (Enciso Gr. upper part of DS 7, Early Aptian; Fig. 21); b) meandering fluvial systems (DS 8: Oliván Group, Late Aptian-Early Albian) (Fig. 22).

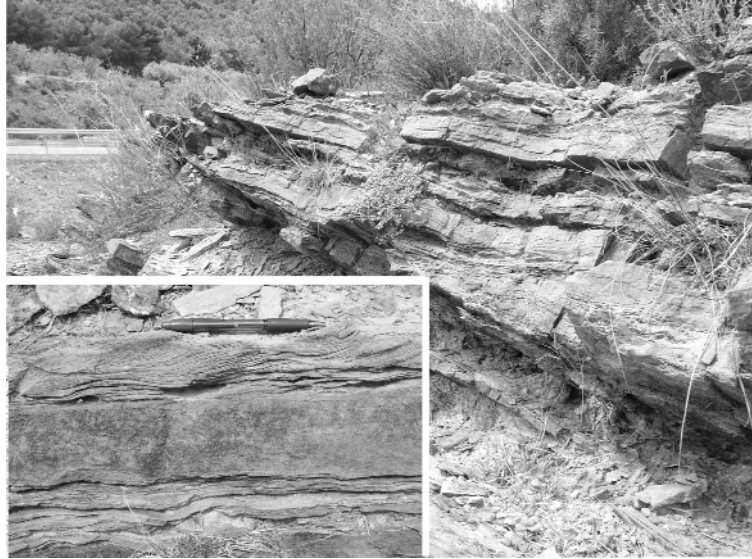


Figure 21. Siliciclastic inputs (crevasse-splay) deposited over carbonate lacustrine facies. Detail of climbing ripples associated with these deposits.

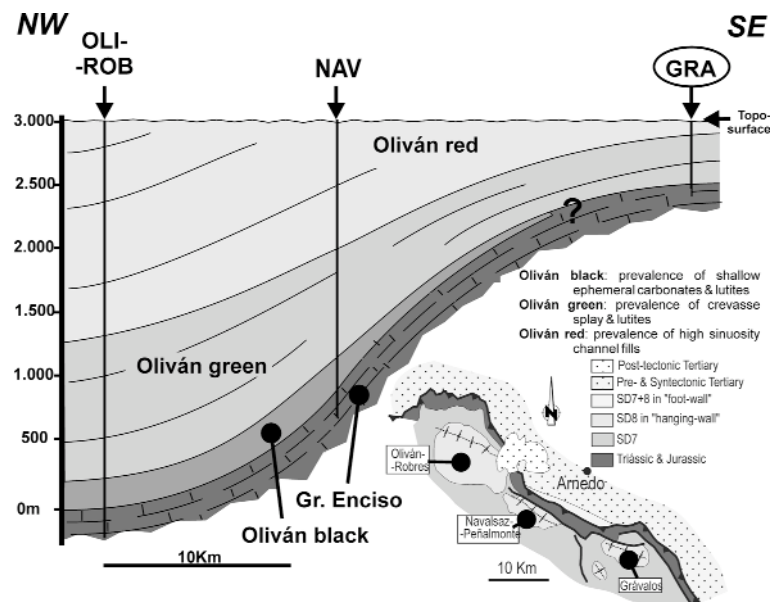


Figure 22. Stratigraphic sections of DS 8 sequence (Late Aptian-Early Albian, Oliván Gr). Note the reduced thickness at the southeastern Grávalos (GRA).  
Modified from Mas et al. (2009).



## Stop 9

*Préjano (La Rioja): The Cameros Northern Thrust. a) Coal rich foot-wall's thrust fluvial-deltaic deposits (DS 8, Late Aptian-Early Albian); b) Hanging-wall's alluvial and shallow lacustrine to coastal carbonates record in the Late Barremian-Early Aptian DS 7 (optional)*

*Location:* On the track located just to the South of Préjano, which connect this locality to the Barranco de las Puertas. UTM coordinates, datum WGS84, zone 30: (a) x=567332; y=4669493 and (b) x=566728; y=4669125 (b) (Figs. 6, 7, 8).

*Objectives:* Fluvial to deltaic deposits with interbedded coal layers (DS 8) and carbonate coastal-lakes and coastal deposits (DS 7).

*Description:* The Cameros Northern Thrust:

a) Fluvial to deltaic (tidal influenced) deposits with interbedded coal layers (Fig. 23) in the foot-wall of the Cameros Northern Thrust (DS 8, Late Aptian-Early Albian).

b) Alluvial deposits and carbonate shallow coastal lakes (Fig. 24) in the hanging-wall of the Cameros Northern Thrust (Jubera and Leza Fms, DS 7, Late Barremian-Early Aptian; optional).

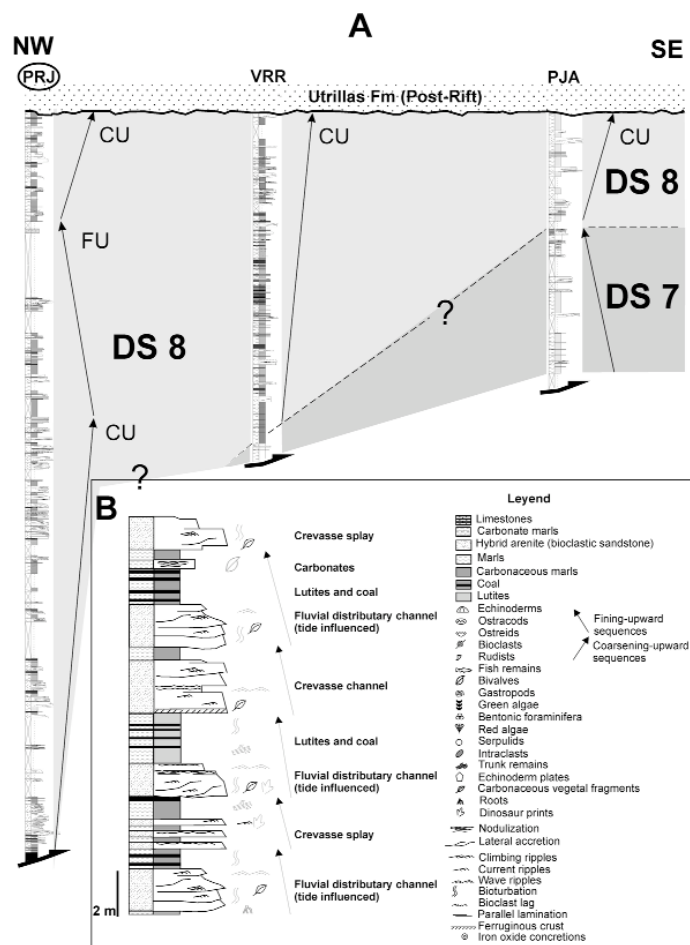


Figure 23. A. The two last syn-rift depositional sequences of the Cameros Basin at the foot wall block of the Northern Cameros Thrust: DS 7 (Late Barremian-Early Aptian) and DS 8 (Late Aptian-Early Albian). DS 7 reaches up to 50 m in thickness and is mainly composed of continental sandstones and lutites, marine limestones and marls. DS 8 is up to 300 m thick and is composed of fluvial-deltaic (tide-influenced) sandstones, lutites and coal beds. B. Characteristic facies of the upper part of DS 8 (Escucha Fm; Late Aptian - Early Albian) at Préjano (hanging wall block of the Northern Cameros Thrust). Modified from Arribas et al. (2009).

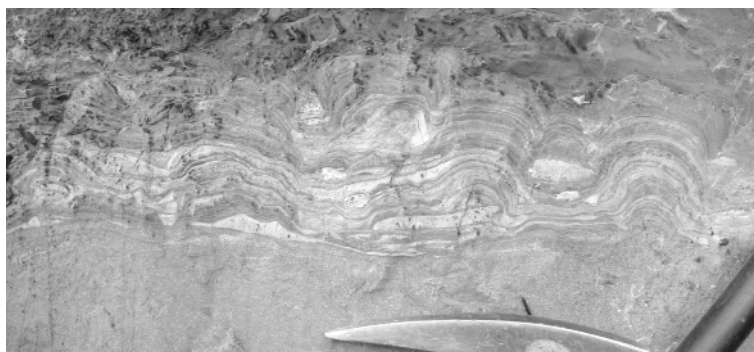


Figure 24. Detail of a stromatolitic layer in the tidal-influenced carbonate facies of the Leza Fm (DS 7, Late Barremian-Early Aptian) at Préjano section (La Rioja).

### **THIRD DAY: THE NORTHERN BORDER OF THE CAMEROS BASIN AND A GENERAL N-S CROSS SECTION ACROSS ITS WESTERN SECTOR**

#### **Stop 10**

*The Leza River Valley (Clavijo-Soto en Cameros, La Rioja): Geometry of the Cameros Northern Thrust and Lacustrine facies in DS 7 (Leza Fm; Barremian-Early Aptian)*

*Location:* On the road LR-250 between the localities of Ribafrecha and Soto en Cameros (La Rioja). UTM coordinates, datum WGS84, zone 30; a) x=549232, y=4688363; b) x=548366, y=4684514; and c) x=547757, y=4682940 (Figs. 6, 7, 8).

*Objectives:* The Snake's Head geometry in the Cameros northern thrust and the lateral facies change between the northern siliciclastic-poor shallow carbonate lacustrine and palustrine facies and the southern siliciclastic-rich lacustrine carbonates.

*Description:* a) DS 7 (Barremian-Early Aptian) at the northern flank of the Snake's Head structure of the Cameros North Thrust front. Panoramic view of the Clavijo section (San Prudencio Convent's ruins) with alluvial fans from the northern margin of the Cameros Basin (Urbión Group D: Jubera Fm), which change upwards to carbonate lacustrine systems (Leza Fm of the Enciso Gr).

b) Panoramic view of active faulting (Fig. 25) during sedimentation of the alluvial fans and carbonate lacustrine systems of DS 7 (Barremian-Early Aptian). Carbonate lacustrine facies of the Leza Fm at the Leza river valley, DS 7) are constituted by shallowing-upwards sequences, which displays abundant palustrine features at the top, such as root traces, brecciation, pseudomicrokarst and mud cracks; Stromatolites, ostracods and charophytes are also frequent (Fig. 26).

c) Panoramic view of the lateral facies change between siliciclastic-poor northern lacustrine-palustrine carbonates of the Leza Formation and the southern siliciclastic-rich lacustrine carbonates.

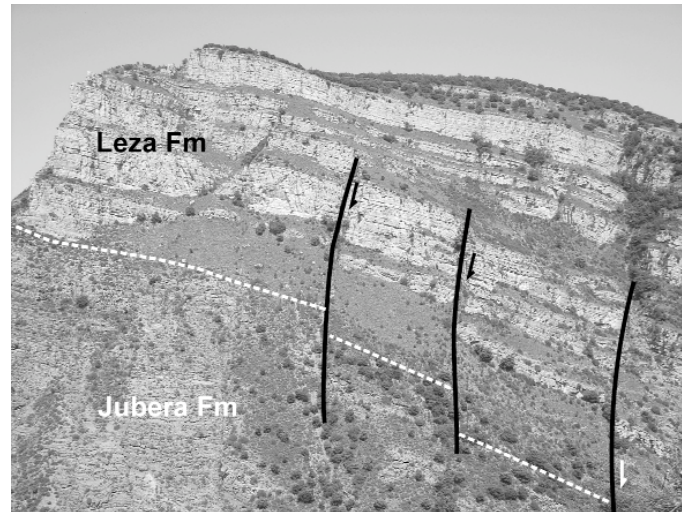


Figure 25. Synsedimentary faults affecting deposits of DS7 (Jubera and Leza Fms) at the Leza River Valley.

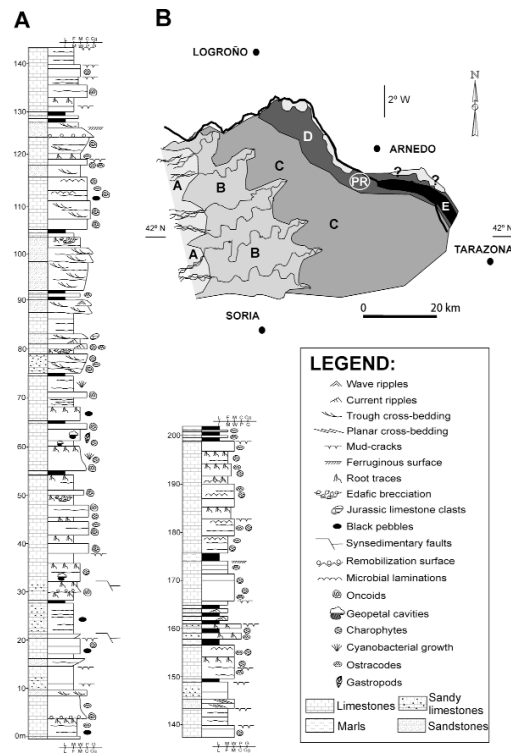


Figure 26. A. Schematic stratigraphic section of Leza Fm (lower part of Enciso Gr; Barremian - Early Aptian) at Leza River valley (La Rioja). B. Paleogeography of the upper part of DS 7 (Barremian-Early Aptian). A y B = Urbión Gr D, Aluvial-fluvial systems (A. proximal; B. distal). C y D = Enciso Gr, Carbonate lacustrine systems (C: with strong siliciclastic influence = Enciso Gr s.s.; D: with very little siliciclastic influence and marine incursions = Leza Fm; E: Carbonate shallow marine inner environments - Early Aptian Urganian carbonate platform). Position of the Leza River valley and Préjano sections (Leza Fm) are shown in the paleogeographic scheme (LZ and PR, respectively). Modified from Mas et al. (2008) and Suárez-González et al. (in press).

## Stop 11

### *Torrecilla en Cameros (La Rioja): Late Jurassic pre-rift coral reef complexes as the substrate of the Cameros Basin*

**Location:** At the Tómalos hermitage, which is located on the road N-111 (Km 300) close to Torrecilla en Cameros. UTM coordinates, datum WGS84, zone 30: x=530583; y=4676129 (Figs. 6, 7, 8).

**Objectives:** The Cameros Basin substrate: the Early Kimmeridgian coral reef complexes of the Torrecilla en Cameros Fm.

**Description:** The Torrecilla Reef Complex consists of a fringing reef composed of several accretionary units. The first ones were deposited along a steep margin and display down-lapping and off-lapping geometries (Fig. 27). In contrast, deposition of the younger accretionary units occurred on a shallow platform where coral reefs were protected from storm waves by long-shore sand bars (Fig. 28, 29). Down-stepping geometries and evolution to progressively shallower environments occurred as a result of a tectonically-forced regression, as the early Kimmeridgian was a period of rising global sea level, which is also apparent in other areas of the Iberian Basin.

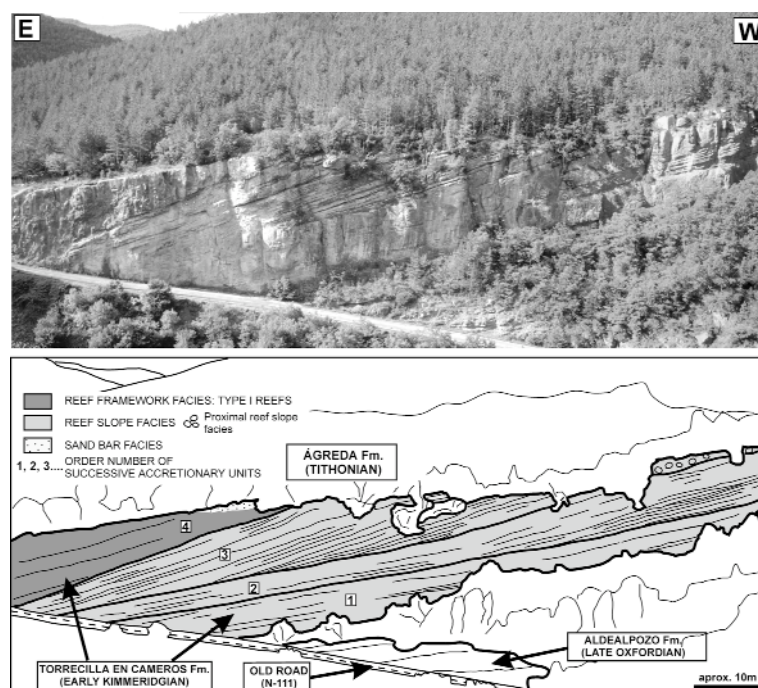


Figure 27. Late Jurassic prograding reef complexes (Early Kimmeridgian, pre-rift) at the town of Torrecilla en Cameros. Note the off-lapping and down-lapping geometries. This reefal unit constituted the substrate for the syn-rift sequences of the Cameros Basin. View from Tómalos hermitage. From Benito and Mas (2006).

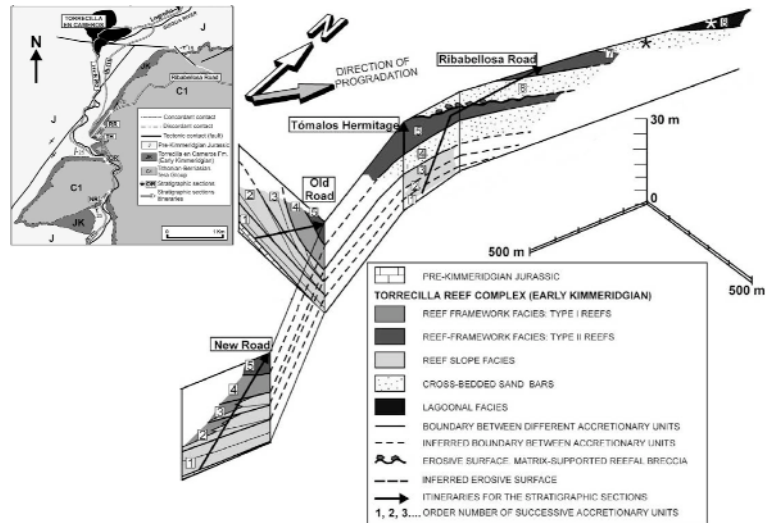


Figure 28. Schematic correlation panel of the stratigraphic sections of the Torrecilla en Cameros Fm at Torrecilla en Cameros area (La Rioja). The attached scheme shows the location of each section. Modified from Benito and Mas (2006).

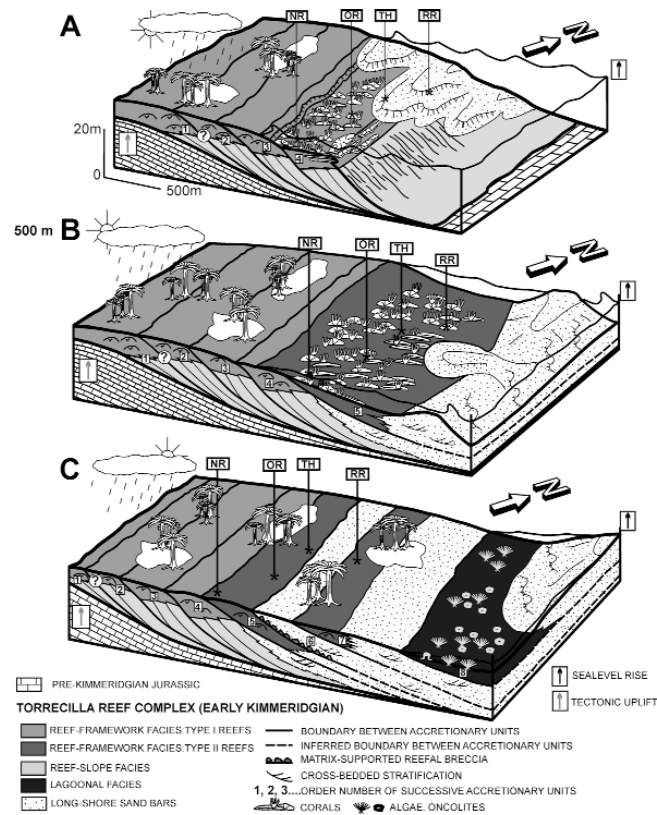


Figure 29. Palaeogeographic reconstructions of the Torrecilla Reef Complex: (A) at the development of the fourth accretionary unit. Note that the horizontal and vertical scale are different, thus, the slope angle is exaggerated. (B) at the development of the fifth accretionary unit; (C) at the development of the eighth accretionary unit. Note location of the 4 stratigraphic sections (NR, OR, TH and RR). From Benito and Mas (2006).



## Stop 12

### *Dam of the Mayor river - Villoslada (La Rioja) - Montenegro (Soria): Stratigraphic section (from top to base) of the first syn-rift sequences DS 3, DS 2 and DS 1 (Berriasian to Tithonian)*

**Location:** On the road LR-333/SO-830 between its intersection with road N-111 and Montenegro de Cameros. Stop at the dam of the Mayor River close to Villoslada de Cameros. UTM coordinates, datum WGS84, zone 30: x=527940, y=4662972 (Figs. 6, 7, 8).

**Objectives:** Lower Cretaceous black shales as possible hydrocarbon source rocks.

**Description:** In this stop we will observe the black shales levels interbedded with lacustrine limestones of the upper part of DS 3 (Berriasian) and flood-plain fluvial sandstone of DS 2 (Tithonian-Berriasian) and will be discussed their role as possible hydrocarbons source rocks (Fig. 30). A general view of the first syn-rift sequences DS 1, DS 2 and DS 3 at the Northwestern area of the Cameros Basin will be obtained very close to the town of Montenegro.

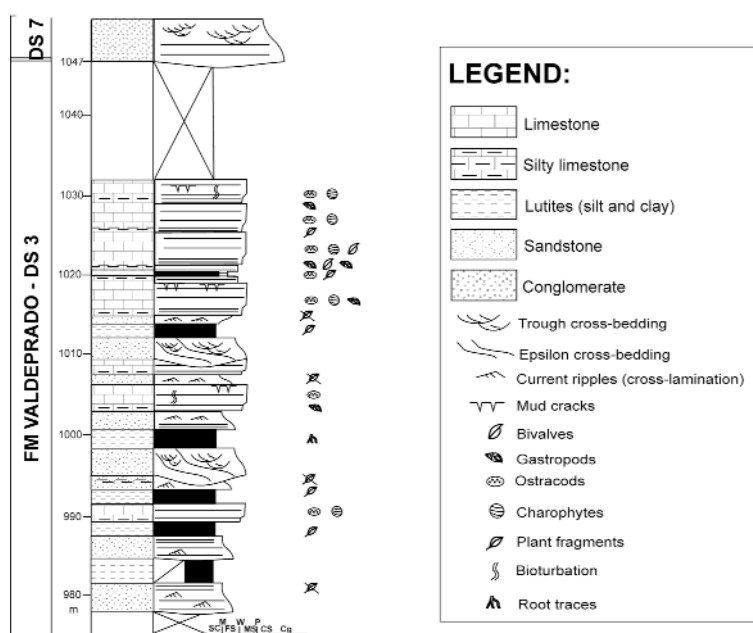


Figure 30. Partial stratigraphic section of the Valdeprado Fm (upper part DS 3; Berriasian) at the dam of the Mayor River (La Rioja). From Montenegro - Villoslada Section.

## Stop 13

*Montenegro – Santa Inés Pass (Soria): the Marine Jurassic substrate with a thick Callovian carbonate rhythmite with black shales*

*Location:* the road SO-830 to Vinuesa (Soria) between Montenegro de Cameros (Soria) and the Santa Inés Pass. UTM coordinates, datum WGS84, zone 30: x=517369; y=4656152 (Figs. 6, 7, 8).

*Objectives:* Potential hydrocarbon source rock in the marine Jurassic substrate of the Cameros Basin. Organic matter-rich layers in the Callovian rhythmite.

*Description:* The Callovian Pozalmuro Fm is represented by the thick rhythmite of limestone and black shales, which were deposited in an outer carbonate ramp. The role of the black shales as possible source rock for hydrocarbons will be discussed.



## Stop 14

### *Santa Inés Pass - Cuerda del Pozo water reservoir – Cidones (Soria): Southwest general stratigraphic section of the syn-rift basin fill. Sandstone source areas and petrofacies*

**Location:** Along the roads SO-830 to Vinuesa (Soria) and SO-820 to Cidones. UTM coordinates, datum WGS84, zone 30: a) At the Santa Inés Pass (Soria) on the road SO-830, x=517796, y=4654016; b) At the Cuerda del Pozo reservoir, x=524749, y=4636122 (Figs. 6, 7, 8).

**Objectives:** The syn-rift sequences and sandstone source areas and petrofacies in the SW Cameros Basin.

**Description:** a) General view of the upper syn-rift sequences at the southwest of the Cameros Basin, (DS 6, Barremian and DS 7, Barremian-Aptian). b) Sandstone composition from the Cameros Basin sedimentary fill and source areas during the main rifting events (Fig. 31). Petrofacies, diagenetic evolution and quality of potential clastic reservoirs. The Late Cretaceous Megacycle (post-rift 2) unconformably overlies the Latest Jurassic-Early Cretaceous Megacycle (syn-rift 2 ).

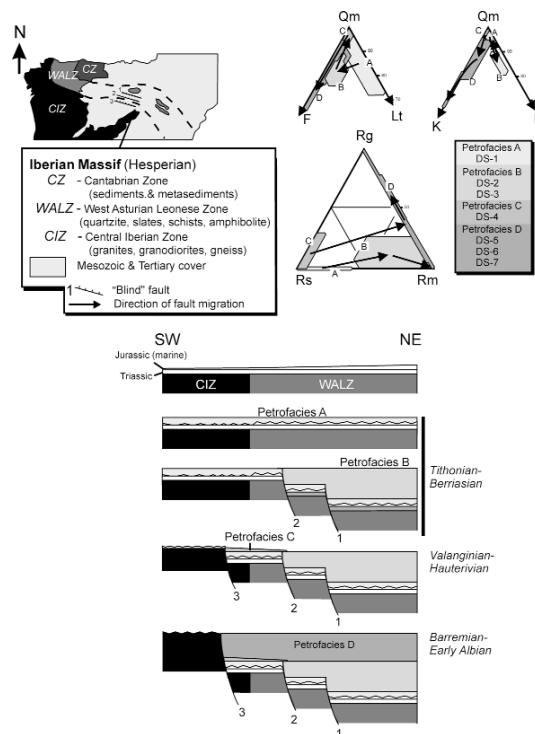


Figure 31. Evolution of sandstone petrofacies during Late Jurassic - Middle Albian clastic deposition in the western Cameros Basin and their genetic relationships with the Iberian Massif zones. Arrows in ternary diagrams show the evolution of petrofacies through time. Note that marine Jurassic deposits are poorly represented in the Central Iberian Zone. Qm: Monocrystalline quartz. F: Feldspar. K: K-feldspar. P: Plagioclase. Lt: Total lithics. Rg: Plutonic/gneissic rock fragment. Rm: Metamorphic rock fragment. Rs: Sedimentary rock fragment. From Arribas et al. (2003).

## Stop 15

### *Picofrentes: tar sands at the base of the Utrillas Fm*

**Location:** This stop is on the track located to the North of the locality of Fuentetoba (Soria), to the Southeast of the Picofrentes peak. UTM coordinates, datum WGS84, zone 30: x = 537029; y = 4625918 (Figs. 6, 7, 8).

**Objectives:** The southern border of the Cameros Basin and the oil seeps in the Late Albian post-rift sandstones.

**Description:** The Southern border of the Cameros Basin is manifested by the inversion of the Cameros South extensional Fault (Fig 32). The base of the Late Cretaceous Megacycle (Post-rift Stage 2), the Utrillas Fm, unconformably overlies the Latest Jurassic-Early Cretaceous Megacycle (syn-rift basin fill). In this area the Utrillas Fm is composed of bituminous sandstones (tar sands) interbedded with mudstone (Fig. 33). As fieldtrip epilogue the Potential Petroleum Systems in the Cameros area (reservoirs, source rocks, oil seeps, and thermal events...) will be discussed.

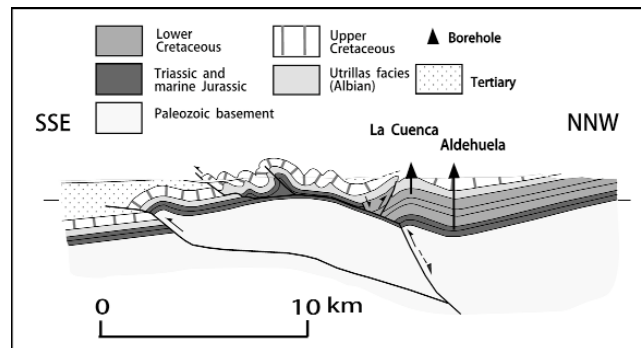


Figure 32. Geological cross-section of the Southern border of the Cameros Basin at the Picofrentes area. For location see Figs. 1B and 5 for location. Modified from Guimerà et al. (1995).



Figure 33. The Picofrentes Peak (Soria). Bituminous sandstones (tar sands) at the base of the Late Cretaceous Megacycle (Utrillas Fm). Fuentetoba-Picofrentes, Soria.

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